Plasma Characterization of a Short-pulse Laser-assisted Pulsed Plasma Thruster

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To observe the effects of the acceleration channel length of the rectangular electrodes of a short-pulse laser assisted pulse plasma thruster (LA-PPT), measurement of magnetic field distributions by magnetic probes were conducted. Temporal variations of magnetic field distributions were measured by magnetic field probes located at various positions for Vc = 8,000 V (C = 50 nF) with thrusters of channel lengths of 50 mm and 5 mm. The magnetic field of shorter channel length was larger than longer one by about 30%. Moreover, by calculating delays when the magnetic field strength reached the local maximums for various positions, traveling speeds of the strong magnetic field regions for channel lengths of 50 mm and 5 mm were 93 km/s and 125 km/s, respectively.

Key Words: Electric propulsion, laser propulsion, pulsed-plasma thruster, laser-assisted pulsed plasma thruster

Nomenclature

l : Acceleration channel length
w : Acceleration channel wide
h : Acceleration channel high
C : Capacitance
V_c : Charging voltage of capacitor

1. Introduction

In resent year, increasing demand of the following small satellite mass 100 kg or less is seen. Especially, the demand for new small propulsion device system development for Drag free control and formation flight is while growing. General propulsion system of small satellites is not only mass limited but also power limited. [1-4)] The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited micro- spacecraft missions. [2-4)] It is effective to use the electrical propulsion system which a specific impulse can expect as promotion system to solve these. Research and development has been promoted for practical use in each country. For example ion engine, pulse plasma thruster etc. pulse plasma thruster is excellent as a propulsion system for attitude control because it can accurately control the impulse. Moreover, it is notice what is thruster suitable for compact satellite. [4)]

On the other hand, small sized onboard laser plasma thruster is also under significant development with rapid evolution of novel compact laser systems. The laser thruster has advantage that they can induce high specific impulses. In addition, the system can be very simple and small with significant controllability of the thrust.[13-16)]

2. Laser Assisted Pulsed Plasma Thruster

A schematic of the rectangular laser-assisted pulse plasma thruster (LA-PPT) is illustrated in Fig.2.[17-18)]

An electrode connected with capacitor that is fully charged. The electrode is configuration as to interpose the solid propellant from the top and bottom. A basic idea of the system is that a bunch of laser-ablation plasma, induced through laser irradiation on a solid target, is supplied to an acceleration channel and additionally accelerated by electrical means between an anode and cathode. When the current between the electrodes increases, the plasma can be heated and further ionized through joule heating. Thus, the electro thermal acceleration effect will be significant. With larger current exceeding more than one thousand amperes, the electromagnetic acceleration effect becomes significant. With the interaction of the current and a self-induced magnetic field, a streamwise acceleration of the plasma will be provided. Discharge current is generated by breakdown between the electrodes.

Since any solid materials can be used for the propellant in these systems, no tanks, no valves, or piping systems are required for the propulsion system. Also, various materials in any phases can be used for the propellant. Therefore, the system employing this technique can be simple and compact. As the laser-ablation plasma has a directed initial velocity of tens of km/s, which will be further accelerated by electrical means, significantly high specific impulses can be expected.

3. Research Motivation

From results of various measurements to date, comparing of discharge of nanosecond pulse and microsecond pulse, nanosecond pulse is large performance of propulsion at the same discharge energy.

Fig. 3 shows the typical impulse bit characteristics of the laser-assisted pulsed plasma thruster replotted from our previous report, in which variations of impulse bit with charge energy are plotted for various acceleration channel configuration. From the Fig 3, it can be seen all the cases that impulse bit increased with the increase of the charge energy. Moreover, thrusters with 10mm×5mm channel length showed higher impulse bit in all the cases.

Therefore, an objective of this study is to observe the mechanism on such a difference in the channel length is to propulsion performance. To observe the self-magnetic field what is occur in acceleration process with magnetic probe. From the time variation of the time-resolved value of magnetic field, time delay of a strong magnetic field area were analyzed and velocity of the plasma were estimated.

4. Experimental set up of Plasma Magnetic Field Measurement

The LA-PPT is placed in vacuum chamber (6.7 ×10-3 Pa) and ignited through a laser ablation plasma induced with a focused laser pulse at a center surface of the propellant. As for the laser oscillator, an Nd:YAG laser (B.M.Industries., 5000 series, wavelength: 1,064 nm, Pulse width: 5 ns, Pulse energy: 400 mJ) was utilized. A specifications ns-LA-PPT of the measurement object is shown in Table.1.

Temporal variations of magnetic field distributions in an acceleration channel, between anode and cathode, were estimated with magnetic probes. A schematic of the experimental setup for the magnetic field measurement is shown in Fig.3. In this study, based on results of Fig.3, thrusters of channel lengths of 50 mm and 5 mm were compared. The magnetic probes were attached on a side wall (glass wall) of the acceleration channel to insulate the probes from the electrodes. Each probe consists of a coil of the core diameter of 2.0 mm (3 turns of enameled copper wire of 1.2 mm in diameter).

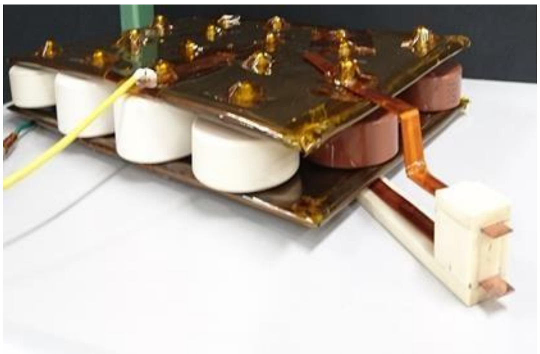

Fig.1. Pulsed plasma thruster

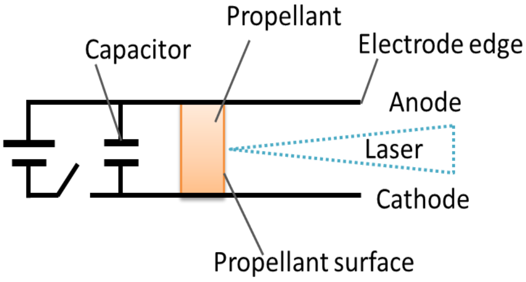

Fig. 2. Schematic of illustration of a rectangular laser-assisted pulsed plasma thruster

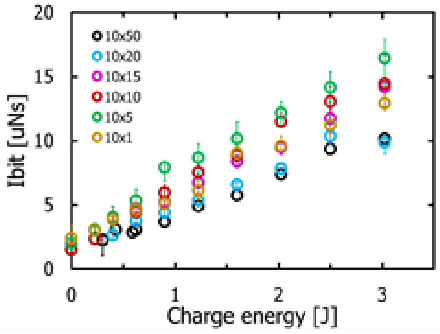

Fig. 3. Variation of impulse bit with charging energy for thrusters with various electrode geometries (electrode length ×electrode height)

Positions of the magnetic probes for the measurement are shown in Fig.5. The first magnetic probe was placed at near surface region of propellant. As shown in this figure, to measure temporal and spatial variations of the magnetic field strengths in the acceleration channels, magnetic probes were attached on an x-stage and displaced to x-direction with arbitraly intervals.

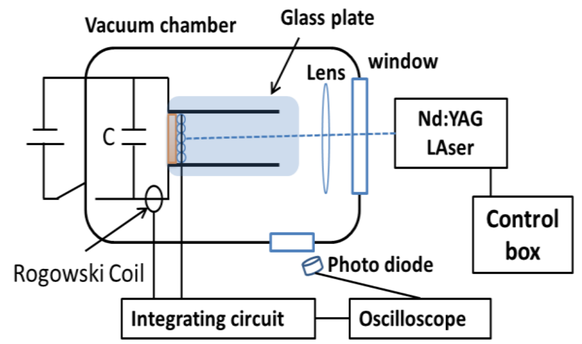

Fig.4. Schematic of the experimental setup for the magnetic field measurement

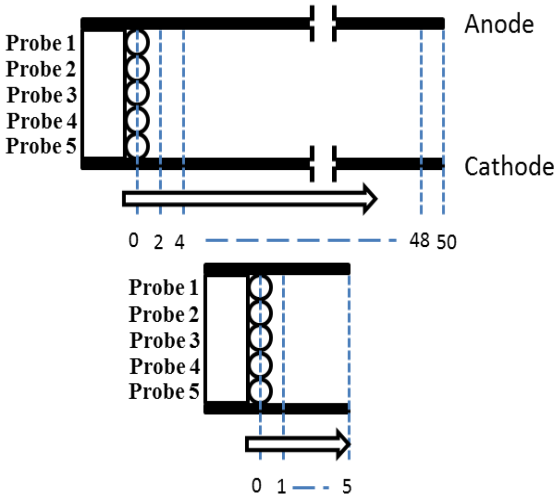

Fig.5. Positions of magnetic probes on side wall of acceleration channel

Fig.6. Magnetic probe

Table 1.   LA-PPT

l[mm]	**50mm&5mm**
w[mm]	**10mm**
h[mm]	**15mm**
Material (electrode)	**Copper**
Propellant	**Al_2O_3**

Table 2. Parameter of magnetic probe

Turn	**3**
Probe diameter	**2×10^{-3}[m]**
Material	**Enamel wire of copper**

5. Results and Discussion

Temporal variations of magnetic fields measured by the magnetic probes located at various positions for *V*c = 8,000 V, *C* = 50 nF are shown in Figs.7 (for channel length of 50 mm, *x* = 0 ~ 8 mm, ⊿*x* = 2 mm) and 8 (for channel length of 5 mm, *x* = 0 ~ 5 mm, ⊿*x* = 1 mm), respectively.

As can be seen, the magnetic fields in the acceleration channel were changing temporally and spatially. In general, it is presumed in PPT operation that the discharge current runs between electrodes forming a current sheet, and the motion of the current sheet is induced by an interaction of the discharge current in the current sheet and the self-induced magnetic field, or namely, Lorentz force.[21] Associated with the motion of the current sheet, the motion of the magnetic fields in the acceleration channel will be induced. Since the magnetic probes are fixed on a side wall of the acceleration channel in this study, temporal variation of the magnetic field monitored with each probe includes positive and negative waveforms of the magnetic field.

From Fig.7, it is shown that there are delays for the first positive (or negative) peaks at probes located at further downstream positions. These delays can be the durations for the magnetic field, or the current sheet, moving in the distances between the probes. Moreover, it can also be seen that temporal variations of the magnetic fields in regions at near propellant surface are almost in phase with a discharge current waveform with a delay of about 100 ns. This implies that a portion of the initial discharge current is probably running at near surface of the propellant.

As can be seen in these figures, the magnetic fields in a whole region of the acceleration channel are induced at 100 ns after induction of discharge current between electrodes. Then, similar to the discharge current waveform, the magnetic field waveforms periodically change with the maximum peak values at propellant surface of ±0.24 T in Fig.7 (for channel length of 50 mm) and ±0.33 T in Fig.8 (for channel length of 5 mm). From these results, it is shown that larger magnetic fields were induced with shorter channel cases.

Values of peak magnetic fields monitored at various positions from these figures are replotted in Fig.9.

As can be seen, values of the magnetic field strengths of shorter channel case are much larger than that of longer channel case. Moreover, a decrease of the magnetic field strength with increasing distances from the propellant surface is more significant in longer channel case than that of shorter channel case. On the other hand, in a shorter channel case, the decrease of the magnetic field strengths with distances is insignificant. This is probably due to larger local current densities in shorter channel case.

By estimating times and delays when the magnetic field strength reach the local maximums at 0 mm and 2 mm, traveling speeds of the strong magnetic field regions can be calculated. From the results, average speeds for channel length of 50 mm and 5 mm are 93 km/s and 125 km/s, respectively. This is probably due to larger local current densities and magnetic field strength, or namely larger Lorentz force, in shorter channel case.

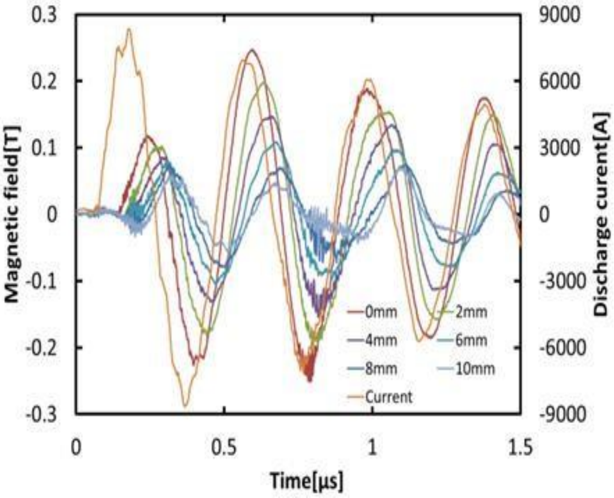

Fig. 7. Probe 3 signal at 0~50mm from propellant surface (Vc =8000V, C= 50nF)

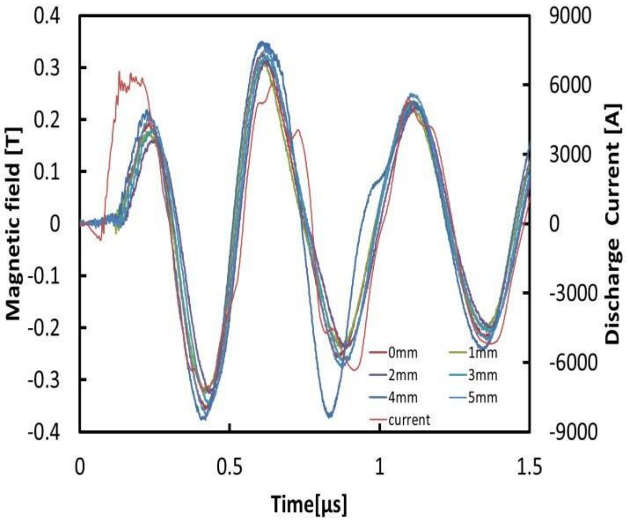

Fig. 8. Probe 3 signal at 0~5mm from propellant surface (Vc =8000V, C= 50nF)

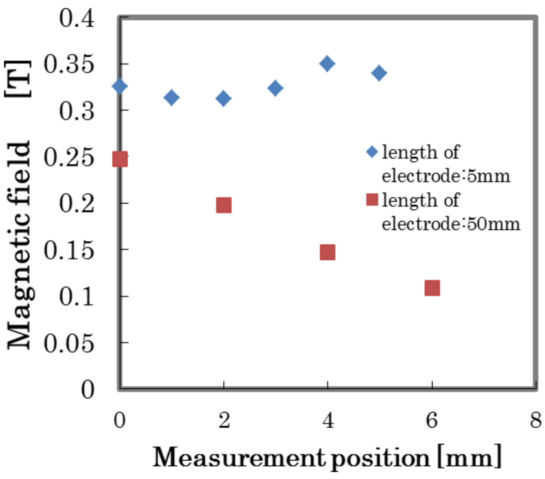

Fig. 9. Peak value of each measurement point (Vc=8000V, C = 50nF, channel length: 5 and 50mm)

6. Conclusion

To observe the effects of the acceleration channel length of the rectangular electrodes of a short-pulse laser assisted pulse plasma thruster (LA-PPT), measurement of magnetic field distributions by magnetic probes were conducted. Temporal variations of magnetic field distributions were measured by magnetic field probes located at various positions for Vc = 8,000 V (C = 50 nF). As for thrusters, channel lengths of 50 mm and 5 mm were compared.

From the result, it was shown that magnetic field of a shorter acceleration channel thruster (5 mm) was larger than that of a long one (50 mm) by about 30%.

Moreover, for the channel length of 50mm, the strength of magnetic field was decreasing with distance from the propellant surface. On the other hand, for the channel length of 5 mm, the strength of magnetic field was constant with all measurement positons.

By estimating times and delays when the magnetic field strength reached the local maximums, traveling speeds of the strong magnetic field regions for channel lengths of 50 mm and 5 mm were 93 km/s and 125 km/s, respectively.

This is probably due to larger local current densities and magnetic field strength, or namely larger Lorentz force, in shorter channel case.

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